# MOVE Annual Meeting / NGVTF 2014 Fall Meeting

# Onboard Storage Projects

Performer & Guest Presentations

5-Minute Overviews

October 15, 2014

# Presentation Schedule

1. **Texas A&M University – Joe Zhou** **\*\*MOVE\*\***
   Vehicular Natural Gas Storage Using Advanced Porous Materials

2. **Ford Motor Company – Mike Veenstra** **\*\*MOVE\*\***
   Covalent and Metal-Organic Framework High-Capacity Natural Gas Adsorption Storage Systems

3. **BlackPak – Doug Kirkpatrick** **\*\*MOVE\*\***
   Containerless Natural Gas Storage

4. **United Technologies Research Center – Ellen Sun** **\*\*MOVE\*\***
   Low Cost Materials and Manufacturing for Conformable CNG Tanks

5. **Otherlab, Inc – Saul Griffith** **\*\*MOVE\*\***
   Conformable Tank CNG Storage

6. **REL, Inc – Adam Loukus** **\*\*MOVE\*\***
   The Matrix Tanks

7. **MeadWestvaco – Brad Reed** **\*\*GUEST\*\***

# Tank Panel Discussion

❖ **Dave Rea – Quantum Technologies**
  Director, Fuel Systems Engineering

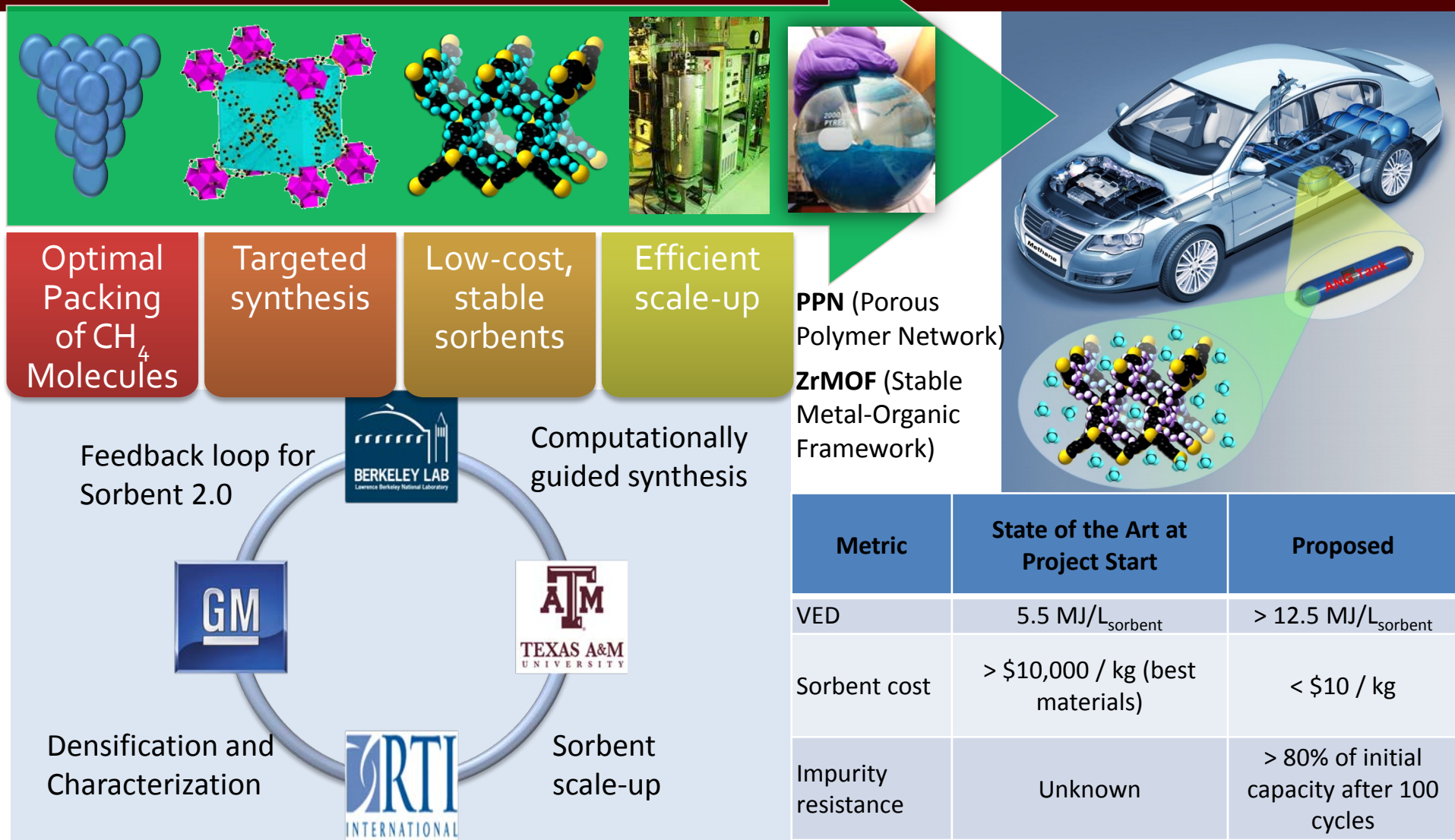❖ **Ken Miller – Worthington Industries**
  Director - Research and Development

# System Development for Vehicular Natural Gas Storage Using Advanced Porous Materials

PI: Prof. Hong-Cai Zhou
zhou@chem.tamu.edu

For more information visit our website:
www.chem.tamu.edu/rgroup/zhou/



**Optimal Packing of $CH_4$ Molecules**

**Targeted synthesis**

**Low-cost, stable sorbents**

**Efficient scale-up**

**PPN** (Porous Polymer Network)

**ZrMOF** (Stable Metal-Organic Framework)

Feedback loop for Sorbent 2.0

Computationally guided synthesis

Densification and Characterization

Sorbent scale-up

| Metric | State of the Art at Project Start | Proposed |
|---|---|---|
| VED | 5.5 MJ/$L_{sorbent}$ | > 12.5 MJ/$L_{sorbent}$ |
| Sorbent cost | > $10,000 / kg (best materials) | < $10 / kg |
| Impurity resistance | Unknown | > 80% of initial capacity after 100 cycles |

# Vehicular Natural Gas Storage Using Advanced Porous Materials

TEXAS A&M UNIVERSITY | BERKELEY LAB — Lawrence Berkeley National Laboratory | RTI INTERNATIONAL | GM

PI: Prof. Hong-Cai Zhou
zhou@chem.tamu.edu

## Goals

| Project Best | | Proposed |
|---|---|---|
| 8.8 MJ/$L_{sorbent}$ (PCN-62) | | > 12.5 MJ/$L_{sorbent}$ |
| ~$50/kg* (PCN-250) | | < $10 / kg |
| 50% of initial capacity after 20 cycles (PPN-4) | | > 80% of initial capacity after 100 cycles |

- Simulation-guided synthesis of Gen2 sorbents with BET >2000 $m^2$/g
- Achieve working capacity greater than 12.5 $MJ_{LHV}$/L and 0.5 $g_{CH4}$/$g_{sorbent}$
- Identify low-cost sorbent synthesis route to approach $10/kg target
- Characterization of Gen2 materials using $CH_4$ and pipeline gas

## Path to Market

**Current Project**
- Pursue opportunity for **niche R&D application**
- Identify **manufacturing/scale-up strategy** for next generation sorbents
- Fully **define value propositions** for ANG sorbents in various markets
- Secure **commercial partnerships** (e.g. materials manufacturing) for next stage funding

**Next Stage**
- Advance **sorbent scale-up, cost, and reliability**
- Integrated **sorbent and tank design** and system modeling
- Small **prototype** demonstration

**Demo & Beyond**
- Near-commercial demo of sorbent + tank technology – **"on-road" tests**
- Demonstration of streamlined NG uptake and release + **efficient heat management**

# Vehicular Natural Gas Storage Using Advanced Porous Materials

PI: Prof. Hong-Cai Zhou
zhou@chem.tamu.edu

## Accomplishments

- 20,000+ structures simulated and bulk sorbent properties predicted

- 30+ candidate MOFs synthesized / characterized

- Scale-up, densification, and low-cost synthesis of several candidate MOFs achieved

- Evaluated MOFs using $CH_4$ sorption tests, pipeline NG cycling tests, and bulk density properties
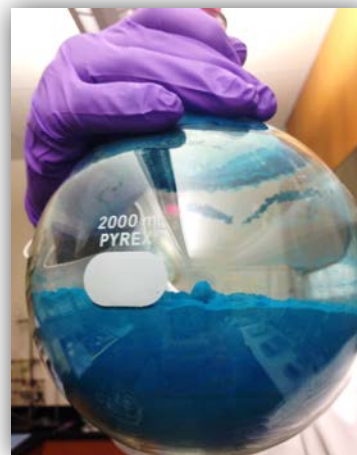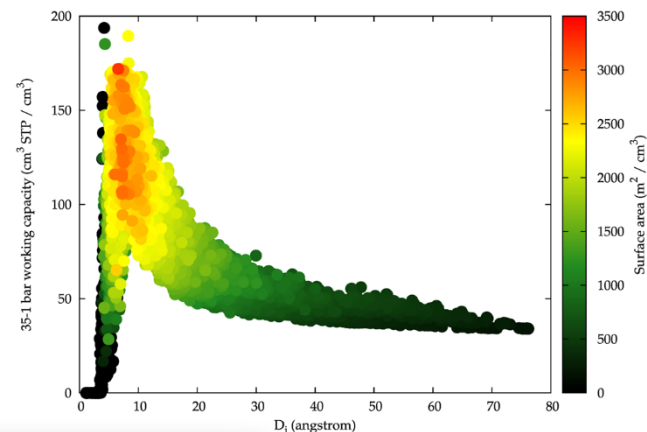
| Metric | State of the Art at Project Start | Project Best | Proposed |
|---|---|---|---|
| VED | 5.5 MJ/L$_{sorbent}$ | 8.8 MJ/L$_{sorbent}$ (PCN-62) | > 12.5 MJ/L$_{sorbent}$ |
| Sorbent cost | > $10,000 / kg (best materials) | ~$50/kg[*] (PCN-250) | < $10 / kg |
| Impurity resistance | Unknown | 50% of initial capacity after 20 cycles (PPN-4) | > 80% of initial capacity after 100 cycles |

# System Overview and Material Property Requirements

## adsorbed natural gas fuel system

**MOVE Program Review**
**11/19/2013**

# Agenda

1. System Overview Requirements

2. Material Data Requirements

3. Vehicle Manufacture Perspective

# ADSORBED NATURAL GAS FUEL SYSTEM OVERVIEW REQUIREMENTS

| Technical System Targets: On-board Adsorbed Natural Gas Fuel System for Light-Duty Vehicles | | | | |
|---|---|---|---|---|
| **Storage Parameter** | **Units** | **Target** | **Level** | **Source** |
| **Volumetric Energy Density:** | **MJ/L (V/V) sorbent** | **12.5 (349)** | **Sorbent** | **Ref[1] - Primary** |
| - Useable energy density [a] | **MJ/L (V/V) inner tank** | **9.2 (257)** | **Inner Tank [b]** | **Ref[1] - Primary** |
| | MJ/L (V/V) system [c] | 7.3 (204) | System | Ref[2] and note [c] |
| **Gravimetric Energy Density:** | **g $CH_4$/g ($cc_{stp}$/g) sorbent** | **0.5 (698)** | **Sorbent** | **Ref[1] - Primary** |
| - Useable energy density [a] | **g $CH_4$/g ($cc_{stp}$/g) inner tank** | **0.4 (559)** | **Inner Tank [b]** | **Ref[1] - Primary** |
| | g $CH_4$/g ($cc_{stp}$/g) system [c] | 0.2 (279) | System | Ref[2] and note [c] |
| **Storage System Cost :** | **$/kg sorbent** | **10** | **Sorbent** | **Ref[1] - Primary** |
| - Based on 10 GGE projected storage | $/ sorbent bed | 500 | Sorbent Bed | Ref[1] |
| | $/ inner tank | 1000 | Inner Tank [b] | Ref[1] |
| | $/ system | 1500 | System | Ref[1] |

[1] DE-FOA-000672: Methane Opportunities for Vehicular Energey (MOVE).

a  Useable energy density targets are based on an inner tank target equivalent to 250 bar methane from Ref[1], which is 9.2 MJ/L and 50 MJ/kg total.  Useable energy density is determined based on the available density between the normal working pressure and minimum delivery pressure at the nominal rated temperature.  For CNG, the nominal rated temperature for determining the useable energy density is 21 C.

b  Inner tank includes the adsorbent, heat exchanger, and other additives to manage the performance of the adsorbent along with packing losses, which has been assumed to be 25% by ARPA-E per Ref[1].

c  System energy density projections are based on a 250 bar Type IV CNG from Ref[1], which indicates a 7.4 MJ/L and 15.6 MJ/kg energy density along with the system additions from Ref[2]. The APRA-E volumetric target for the system is based on the energy of the fuel divided by the volume of the smallest rectangular cuboid that encloses the tank.

# ADSORBED NATURAL GAS FUEL SYSTEM OVERVIEW REQUIREMENTS



**Small Car Example**

- Lighter natural gas tank leads to a lighter overall fuel system

| | Type IV Tank | Type I Steel Tank |
|---|---|---|
| CNG Tank | 32 kg | 105 kg. |
| Fuel | 13 kg. | 13 kg. |
| Brackets | 5 kg. | 21 kg. |
| Spare Tire | N/A | 9 kg. |
| Total Weight: | 50 kg. | 148 kg |
| | (<5% of vehicle wt) | |

[2] N. Sirosh, Quantum Technologies. Compressed Natural Gas On-Board Storage: ARPA-E NATURAL GAS VEHICLE TECHNOLOGIES WORKSHOP, January 26, 2012. In addition for complete on-board system comparison, an estimated 20 kg and 10 liters was included for complete system evaluation based on OEM input.

| | FOA Reference | 10 GGE Scale |
|---|---|---|
| **CNG Tank Type IV 250 bar** | 42 kg | 59 kg |
| **Fuel** | 19 kg (8 GGE) | 24 kg (10 GGE) |
| **Total:** | 62 kg | 73 kg |
| **Gravimetric** | 31% (15.6 MJ/kg) | 29% (14.4 MJ/kg) |
| **System** | 20 kg | 20 kg |
| **System Total:** | 82 kg | 93 kg |
| **Gravimetric** | 24% (11.7 MJ/kg} | 23% (11.6 MJ/kg) |
| **Volumetric** | 148 g/liter (7.4 MJ/liter) | 148 g/liter (7.4 MJ/liter) |
| **System** | 10 liters | 10 liters |
| **Volumetric** | 137 g/liter (6.9 MJ/liter) | 145 g/liter (7.3 MJ/liter) |

## Technical System Targets: On-board Adsorbed Natural Gas Fuel System for Light-Duty Vehicles

| Storage Parameter | Units | Target | Level | Source |
|---|---|---|---|---|
| **Durability/Operability:** | | | | |
| • Operating ambient temperature | °C | -40/60 | System | **Ref[1] - Secondary** / Ref[3] |
| • Min/max delivery temperature | °C | -40/85 | System | **Ref[1] - Secondary** |
| • Min/max desorption temperature | °C | TBD/85 | Inner Tank | Ref[4] / **Ref[1] - Secondary** |
| • Min/max adsorption temperature | °C | TBD/TBD | Inner Tank | Ref [4] |
| • Nominal rated temperature | °C | TBD | Inner Tank | Ref [4] |
| • Demonstration cycle life [d] | Cycles | 100 | System | **Ref[1] - Secondary** and note [d] |
| • Operational customer cycle life [d] | Cycles | 1000 | System | Ref[1] and note [d] |
| • Max Degradation after cycle life | Initial Capacity | 80% | Inner Tank | Ref[1] |
| • Min delivery pressure to engine [e] | bar (abs) | 5 | System | Ref[1] and note [e] |
| • Nominal working pressure | bar (abs) | TBD | System | Ref [4] |
| • Max operating storage pressure | bar (abs) | TBD | System | Ref [4] |

[3] The highest recorded ambient temperature (excluding oven effect from sun load) in the world is 56.7°C recorded at Death Valley, CA, USA in 1913. Court, A. *How hot is Death Valley?* Geographical Review, 39, pp. 214-220, 1949.

[4] The operating temperature and pressure are indicated as "TBD" since these values can be determined by the system designer based on a multi-variable optimization of the other requirements in this document.

d Demonstration life time is based on expected cycle testing within the project duration (3 years) while the actual customer usage life cycles is 1,000 based on the assumption of 50 fills per year and a 20 year lifetime by Ref[1]

e In the US and Europe, the typical CNG injector is the Bosch NGi2. In most cases, inlet pressure used for these injectors is around 5 to 8 bar but in some cases 10 bar is used to get enough flow rate through it. In other parts of the world, CNG engines are non-boosted and utilize a fuel delivery pressure of 3.5 bar.
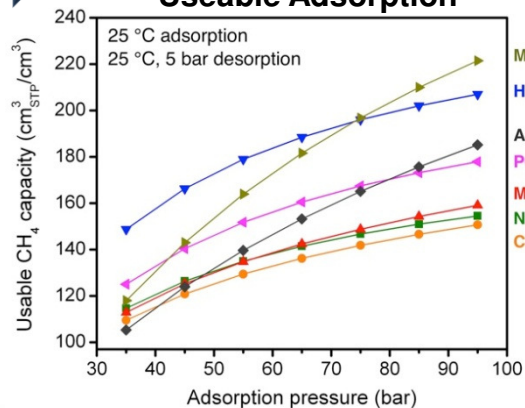
# ADSORBED NATURAL GAS FUEL SYSTEM OVERVIEW REQUIREMENTS



## Usable Capacity
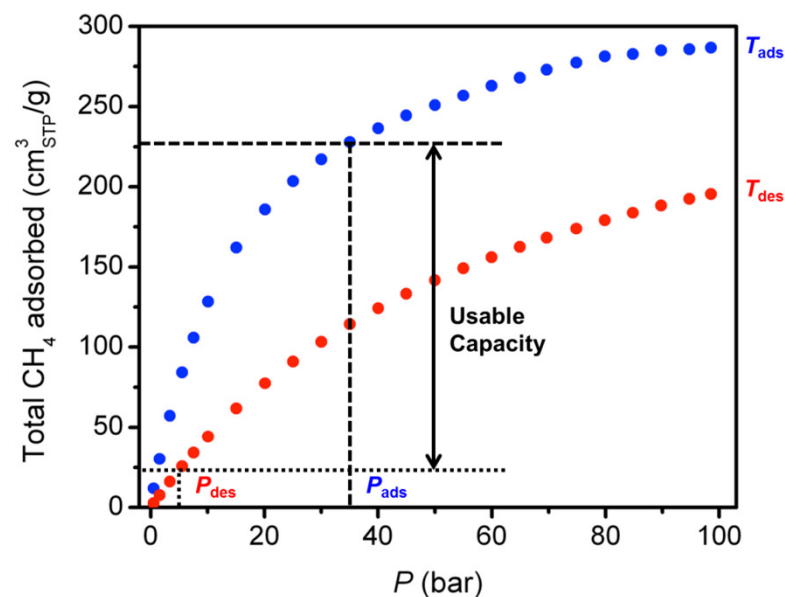


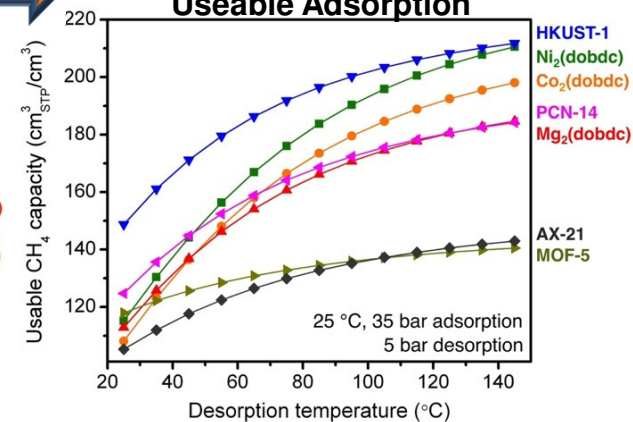### Gen0 Volumetric Total Adsorption



### Gen0 Volumetric Useable Adsorption



### Gen0 Volumetric Useable Adsorption

| Technical System Targets: On-board Adsorbed Natural Gas Fuel System for Light-Duty Vehicles | | | | |
|---|---|---|---|---|
| **Storage Parameter** | **Units** | **Target** | **Level** | **Source** |
| **Charging / Discharging Rates:** | | | | |
| • System fill time (10 GGE) | min | 3 - 5 | System | Ref[5] |
| • Specific desorption flow rate [f] | kg/h-L (g/s) | 0.2 (7.8) | System | **Ref[1] - Secondary** and note [f] |
| • Max. start time to full flow (-30°C) | s | 10 | System | Ref[6] |
| • Max. start time to full flow (-20°C) | s | 5 | System | Ref[6] |
| • Max. start time to full flow (0°C) | s | 3 | System | Ref[6] |
| **Fuel Quality** (to/from storage): | mol% | See note [g] | System | **Ref[1] – Secondary** and note [g] |
| **Environmental Health & Safety:** | | Meets or exceeds applicable standards [h] | System | **Ref[1] - Secondary** and Ref[6] |
| • Permeation & leakage | Scc/h | | | |
| • Toxicity | - | | | |
| • Safety and Stability | - | | | |

[5] The filling target is designed to achieve current customer experience. Currently, gasoline vehicles are filled in about 3 to 5 minutes, with small vehicles taking less time and large ones more time.

[6] Ford Motor Company Qualified Vehicle Modifier Bulletin - Gaseous Fuels Unique Guidelines and Requirements, August 16, 2012.

f  Desorption flow rate needs to be provided over the entire range of useable capacity and is based on a 150 hp engine at 30% efficiency and 47.7 kW energy content in 1 g/s of natural gas.  The 150 hp is based on a compact vehicle while additional flow rate would be required for a full-size vehicle such as 19 g/s for 365 hp.

## Fuel Quality

*SAE J1616 highlights (refer to the current standard as the official reference) for fuel composition and quality.*

*Water content*: The local dewpoint temperature of the fuel should be 5.6° C below the monthly lowest dry-bulb temperature at the maximum operating cylinder pressure. The margin of 5.6° C is intended to prevent hydrate blockage due to pressure reduction at various stages in the vehicle fuel system.

*Carbon dioxide*: Given that the corrosive environment is controlled via the limited water concentration, no limits are required on the concentration of $CO_2$ for this purpose. Rather, a limit of 3.0% $CO_2$ by volume is recommended to help maintain stoichiometry.

*Sulfur compounds*: The total content of sulfur compounds, including odorants, should be limited to 8-30 ppm by mass to avoid excessive exhaust catalyst poisoning.

*Methanol*: No methanol shall be added to natural gas at the CNG refueling station. Methanol can cause corrosion of natural gas cylinders and deterioration of fuel system components.

*Oxygen*: Given that the corrosive environment is controlled by the limited water concentration, no limits are required on the concentration of oxygen for the control of corrosion. On the other hand, the oxygen level must not produce a mixture within the flammability limits of natural gas.

*Particulate and foreign matter concentration* should be minimized to avoid contamination, clogging and erosion of fuel system components. CNG fuel delivered to the vehicle should have particulate matter content equal to or less than 5 mm (micron) in size.

*Oil content:* Additional data are required to determine acceptable lubricating oil levels as well as standardized test procedures for quantifying lubricating oil content. Lubricated compressor oil levels should be monitored and coalescing filters may be installed downstream of the compressor discharge to control oil.

*Hydrocarbon dewpoint temperature:* The composition of natural gas should be such that the original gaseous storage volume will form less than 1% of a liquid condensate at the lowest ambient temperatures and gas storage pressure between 5.5 and 8.3 MPa, at which maximum condensation occurs, depending on gas composition.

# ADSORBED NATURAL GAS FUEL SYSTEM OVERVIEW REQUIREMENTS

| Component | Range[1] (mol %) | Typical[1] Analysis (mol %) | DTE[2] Analysis (mol %) | GTI[3] Analysis (mol %) | CARB Natural Gas CERT SPEC[4] | Germany:DIN 51624:2007 Fuel Spec | ARPA-E FOA Ref[1] |
|---|---|---|---|---|---|---|---|
| Methane ($CH_4$) | 87.0 - 97.0 | 95.0 | 95.5 | 93.4 | 88.0 | 80 | |
| Ethane ($C_2H_6$) | 1.5 – 7.0 | 3.2 | 2.23 | 3.20 | 6.0 | 12 | < 5 |
| Propane ($C_3H_8$) | 0.1 - 1.5 | 0.2 | 0.37 | 0.69 | 3.0 $C_3$ and higher | 6.0 | < 1 |
| iso – Butane ($C_4H_{10}$) | 0.01 - 0.3 | 0.03 | 0.05 | 0.00 | | -- | |
| normal – Butane ($C_4H_{10}$) | 0.01 - 0.3 | 0.03 | 0.07 | 0.25 | | 2.0 | |
| iso – Pentane ($C_5H_{12}$) | trace - 0.04 | 0.01 | 0.03 | 0.00 | | -- | |
| normal – Pentane ($C_5H_{12}$) | trace - 0.04 | 0.01 | 0.02 | 0.10 | | 1.0 | |
| Hexanes ($C_6H_{14}$) plus | trace - 0.06 | 0.01 | 0.05 | 0.06 | 0.2 $C_6$ and higher | 0.5 | |
| Nitrogen ($N_2$) | 0.2 - 5.5 | 1.0 | 0.62 | 1.50 | 1.5 – 4.5 (N2+$CO_2$) | 15.0 (N2+$CO_2$) | |
| Carbon Dioxide ($CO_2$) | 0.1 - 1.0 | 0.5 | 1.08 | 0.80 | | -- | < 1 |
| Oxygen ($O_2$) | 0.01 - 0.1 | 0.02 | 0.00 | 0.00 | 1.0 | 3.0 | |
| Hydrogen ($H_2$) | trace - 0.02 | trace | 0.00 | 0.00 | 0.1 | 2.0 | |
| Sulfur | 5.5 mg/m$^3$ | | | | | 10 mg/kg | < 20 ppm |
| Water Content | 16 - 32 mg/m$^3$ | | | | | 40 mg/kg | < 100 ppm |

2 Michigan Consolidated Gas Company Laboratory Gas Analysis Report for natural gas sample at CNG fueling facility, Jan. 2010

3 Light Duty CNG Vehicle Fuel Consumption Study Topical Report, GTI Project Number 20245, April 2006

4 California Air Resource Board Specification for Compressed Natural Gas (13 CA ADC § 2292.5)

## DTE LAB SERVICES – GAS ANALYSIS REPORT FROM MICHIGAN CNG STATIONS (9/2013)

| Component | Average (mol %) | Std Dev (mol %) | Test Gas (mol %) |
|---|---|---|---|
| Methane ($CH_4$) | 95.562 | 0.865 | 95.98 |
| Ethane ($C_2H_6$) | 2.363 | 0.707 | 2.568 |
| Propane ($C_3H_8$) | 0.161 | 0.115 | 0.3395 |
| iso – Butane ($C_4H_{10}$) | 0.014 | 0.012 | 0.0779 |
| normal – Butane ($C_4H_{10}$) | 0.019 | 0.014 | 0.0779 |
| iso – Pentane ($C_5H_{12}$) | 0.008 | 0.007 | 0.020 |
| normal – Pentane ($C_5H_{12}$) | 0.004 | 0.001 | 0.020 |
| Hexanes ($C_6H_{14}$) plus | < .001 | < .001 | .0150 |
| Nitrogen ($N_2$) | 0.694 | 0.429 | -- |
| Carbon Dioxide ($CO_2$) | 1.157 | 0.271 | .9995 |
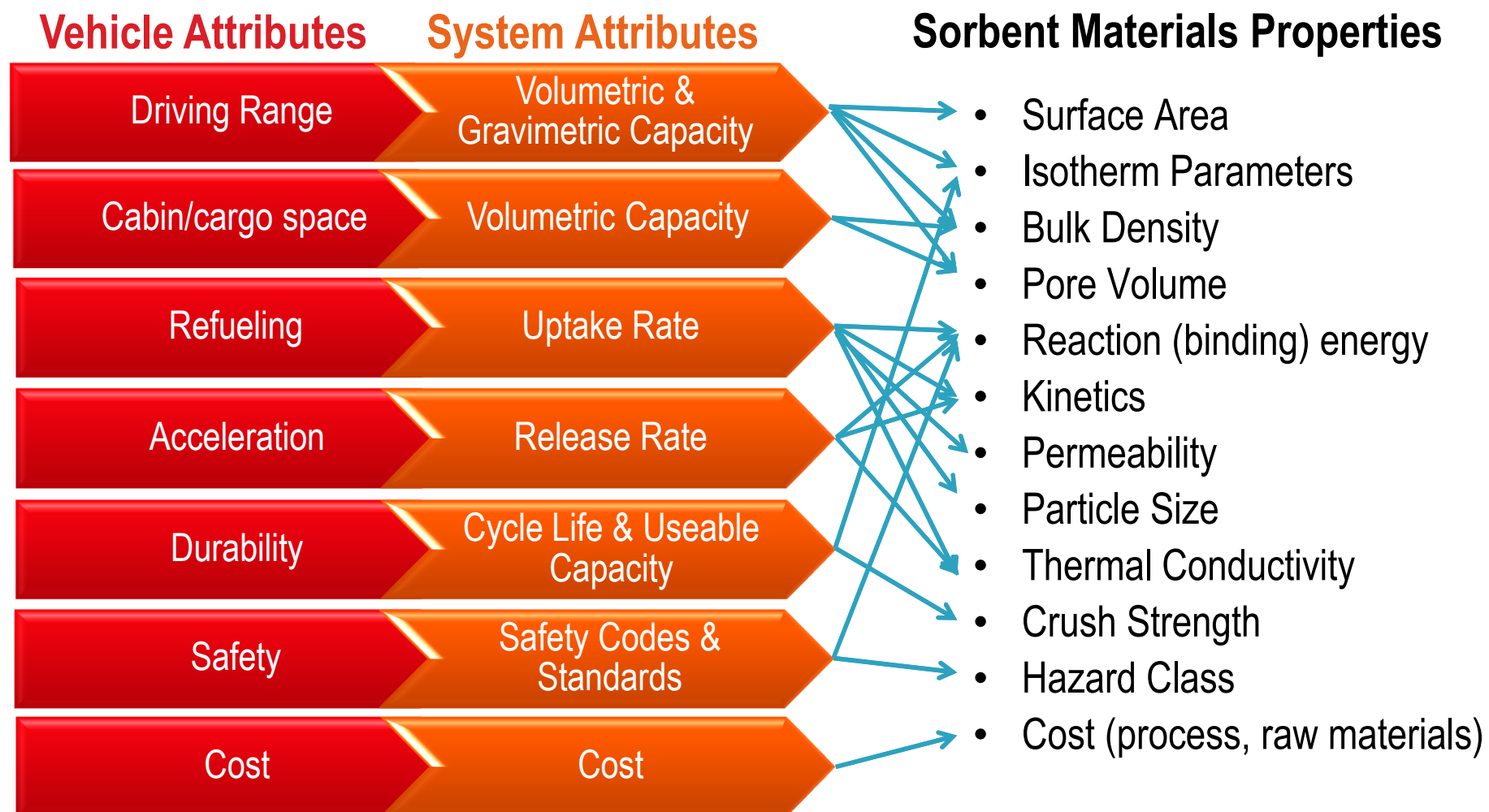
1. **Isotherms of excess adsorption, $n_{ex}$, vs pressure, *P***
   a. A <u>minimum</u> of five isotherms at temperatures evenly distributed over the range 195<T<525K.
      i. The temperature must be kept constant to within ±2 K throughout the test sequence
      ii. Test pressures should range between $5 < P < 100$ bar at an incremental pressure resolution of 5 bar
      iii. The gas composition should ideally be pure methane for comparison purposes. The gas composition should be high quality (99.999% purity)
      iv. Natural gas data will also be accepted with the gas composition detailed with species given to the highest accuracy known
      v. It is suggested that tests be performed in accordance with the Best Practices Guide given in Ref. 1, which includes measuring background $CH_4$ adsorption isotherms for empty sample holders (or sample holders containing a nonadsorbing material) under identical experimental conditions to confirm the adsorption instrument is producing high quality data

2. **Crystal Density**
   a. Determine using diffraction techniques. Provide complete crystal structure that was used to determine density.  Note that the crystal structure should be representative of the state of the material during $CH_4$ adsorption (i.e. near ambient temperature and fully desolvated).

3. **Pore Volume**

   a. Determine using a $N_2$ adsorption isotherm at 77 K. Specify the isotherm model or $P/P_0$ that was used to calculate pore volume.

4. **Bulk Powder Tap Density**

   a. Determine physically on as large a sample as possible using a slight "tapping" to consolidate the powder (indicate sample size and number of taps).

5. **Surface Area**

   a. Determine with BET and/or Langmuir theory using a $N_2$ adsorption isotherm at 77 K.

6. **Skeletal Density**

   a. Determine using He displacement at room temperature.

7. **Specific Heat**

   a. Determine through calorimetry with $CH_4$ for temperatures ranging from 170 K to the maximum temperature at which the material is stable

8. **Thermal conductivity of compact**

   a. Determine at room temperature using as low a density compact as possible to retain shape

9. **Thermal Stability**

   a. Maximum temperature at which material shows initial loss in porosity over ~12 hours.

10. **Chemical Stability**
    a. Evaluate chemical compatibility of the material by conducting isotherm measurement after initial exposure and multiple cycles (~100) with common natural gas impurities (either as a composite or preferably in isolation) such as $C_xH_{2x+2}$, $CO_2$, $O_2$, $H_2$, S, $H_2O$, etc.
11. **Precursors, solvents, and synthesis/activation conditions**
    a. Describe relative amounts to be used to establish a baseline for cost comparison
12. **Densified media**
    a. Specify if a binder is required for compacted material stability
    b. Provide data variations (for excess adsorption, pore volume, and thermal conductivity at a minimum) for at least 3 compaction densities between the low density necessary to retain shape and below the crystal density.  as a function of changes in density

**Ford has released a Qualified Vehicle Modifier (QVM) Bulletin Q-185R1 that provides guidance on modifying Ford Gaseous Prep Engines. The bulletin is updated as required and contains the following information:**
• Modifier responsibilities for required government emission and safety (FMVSS) certification
• Modifier responsibilities for warranty of the new or modified fuel system components
• Modifier required information to the customer to explain CNG/LPG fuel system operation and maintenance, identify unique components associated with the CNG/LPG conversion, and provide contacts for parts and service of the CNG/LPG fuel system

## From dealer order through customer delivery

1. Dealer and customer determine appropriate vehicle based on application, payload and range

2. Dealer places vehicle order, and vehicle is delivered to modifier

3. Modifier installs alternative fuel components and system

4. Vehicle is delivered to dealer and dealer delivers vehicle to customer

| QVM | | | | | | |
|---|---|---|---|---|---|---|
| **BAF** | CNG | CNG | CNG | CNG | CNG | CNG |
| **Venchurs** | | | CNG | | | |
| **LandiRenzo** | | CNG | CNG | CNG | CNG | CNG |
| **IMPCO** | CNG | CNG | CNG | CNG | CNG | CNG |
| **Westport LD** | | | CNG | CNG | | |
| **Altech-Eco** | CNG | CNG | CNG | | | |

# Challenges of CNG

- **Lower energy density → lower vehicle mileage & unfavorable package**

- **Additional weight of fuel tanks**

- **Upfit costs**

- **Energy losses for gas compression**

- **Fueling station costs**

- **Lack of fueling station infrastructure**

# Gravimetric vs. Volumetric Capacity

- Isolate effects of changes in gravimetric and volumetric capacity on vehicle driving range

1) Gravimetric case

- Assume 10 GGE vehicle, constant volumetric capacity, base capacity equal to HKUST-1

- Changes in gravimetric capacity affect fuel economy: ± 45 kg → 2% fuel economy

2) Volumetric case

- Assume a fixed volume available for fuel tank, constant gravimetric capacity
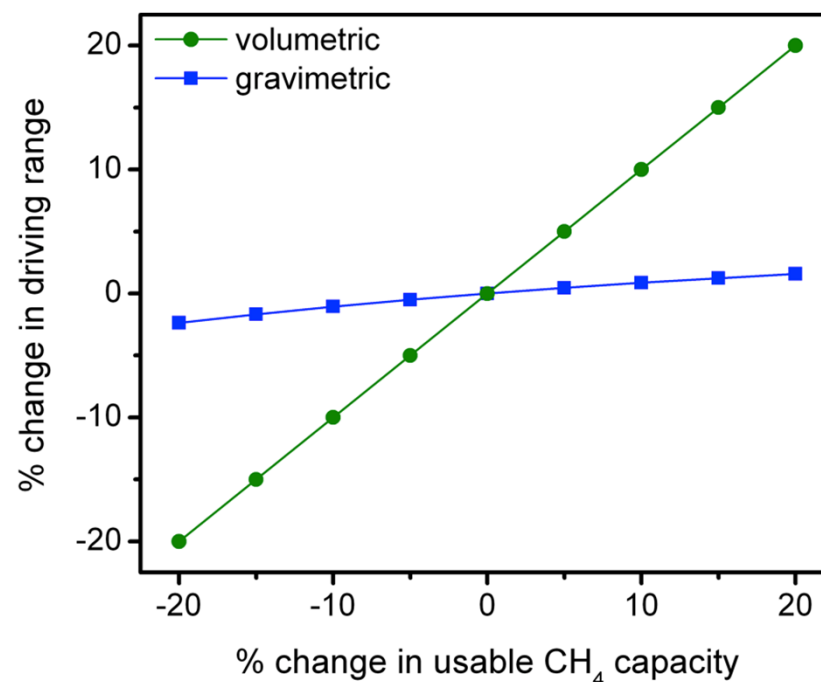
# Summary

1. **System Overview Requirements**
   - *Volumetric Energy Density, Gravimetric Energy Density and Cost*
   - *Durability/Operability*
   - *Charging / Discharging Rates*
   - *Fuel Quality*
   - *Environmental Health & Safety*

2. **Material Data Requirements**
   - *Isotherm data, crystal density, and pore volume*
   - *Bulk density, thermal conductivity, stability, and densification effects*

3. **Vehicle Manufacture Perspective**
   - *Key Parameter: Cost*
   - *Key for Driving Range: Volumetric Energy Density*

# Containerless Natural Gas Storage

BlackPak Inc., Entegris, SRI International
Dr. Doug Kirkpatrick, PI (CEO BlackPak)
Tel: 415-273-6808
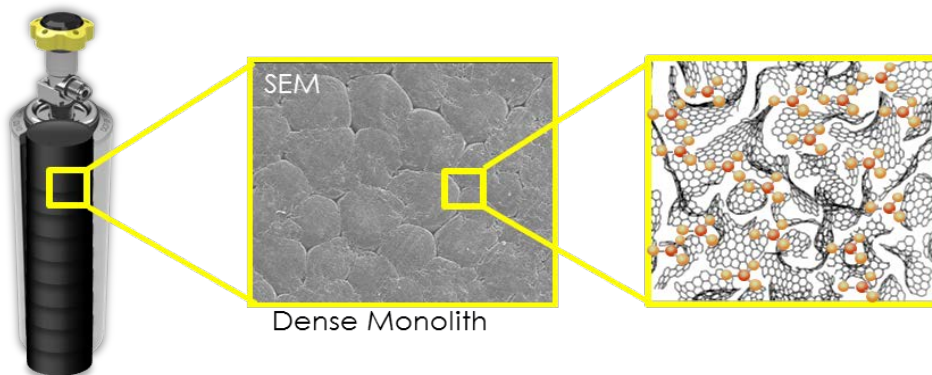Email: dkirkpatrick@blackpaktech.com

# Containerless Natural Gas Storage

BlackPak, Entegris, SRI International
Dr. Doug Kirkpatrick, PI (CEO BlackPak)
Tel: 415-273-6808
Email: dkirkpatrick@blackpaktech.com

## Innovation

➢ **Leverage ultra-microporous carbon monolith materials technology**
  o Enable use of commodity precursors: sorbent cost → < $5/kg
  o Enable alternative tank approaches: conformability > 85%, minimize container cost and structure

➢ **Leverage sorbent properties to perform as both tank *and* pump**
  o Reduce off-vehicle pump requirement to single-stage compression (reduce cost)
  o Access full storage capacity of sorbent

➢ **Target <u>total</u> system cost < $4000**
  o Inclusive of sorbent, tank, pump, thermal management system, and integration
  o Commercial customer payback < 12 months
  o Consumer payback < 24 months



SEM

Dense Monolith

*Pyrolized PVDC produces a highly ordered and folded carbon. Reproducing this structure with low cost commodity feedstock is a central innovation.*

# Containerless Natural Gas Storage

BlackPak, Entegris, SRI International
Dr. Doug Kirkpatrick, PI (CEO BlackPak)
Tel: 415-273-6808
Email: dkirkpatrick@blackpaktech.com

## Objectives

➢ Sorbent cost < $5/kg
- o Maintain V/V ≥ 150
- o Cycle life > 1000 cycles at 80% capacity
- o Approach
  - Detailed understanding of why PVDC works
  - Select commodity precursor materials
  - Optimize process configuration & conditions

➢ Specific desorption rate >0.5 kg/h-L
- o Optimize carbon monolith internal structure
  - Permeability
  - Thermal conductivity & strength
- o Optimize carbon monolith sizing & shape
  - Assembly-to-shape
  - Manufacturability-to-cost
  - Surface area
  - System thermal conductivity & strength

➢ Conformability factor >85%

➢ Enable reduced fill pump costs

| Parameter (Cat. 2 unless otherwise noted) | Project Target | MOVE Program Target |
|---|---|---|
| **Cost** | | |
| On board storage | <$150/GGE | $150/GGE |
| On-site refueling (Cat. 4) | <$500 | $500 |
| Sorbent | $5/kg <$100/GGE | <$10/kg N/A |
| **Performance** | | |
| Volumetric energy density | >6MJ/L | >9.2MJ/L |
| Tank volume | 20 L (min) | 6 L |
| Operating pressure | 500 PSI | N/A |
| Lifetime | >1000 cycles | 100 cycles |
| Desorption temperature | < 85 C | < 85 C |
| Temperature tolerance | -40 to 85 C | -40 to 85 C |
| Impurity tolerance | Pipeline NG | Pipeline NG |
| Safety | Full regulatory compliance | Tolerant of abusive conditions & physical damage |
| Conformability factor (Cat. 3) | >85% | >90% |
| Specific desorption rate | 0.54 kg/h-L | 2.6 kW/L (0.2 kg/h-L) |
| Fill rate (pump mode) (Cat. 4) | >1 GGE/h | 1 GGE/h |

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# Containerless Natural Gas Storage

BlackPak, Entegris, SRI International
Dr. Doug Kirkpatrick, PI (CEO BlackPak)
Tel: 415-273-6808
Email: dkirkpatrick@blackpaktech.com

## Planned Activities

➤ **Low-cost carbon downselect Q1/2015**
- Downselect to 3 materials-process combinations
- Select primary focus for prototype development
- Drivers
  - Performance per unit cost
  - Diverse & commoditized supply chain
  - Amenable to scaling via contract mfg.

➤ **Concept demonstration Q1/2015**
- "Lab queen" concept tank on golf course mower
- Target
  - 1-2 GGE
  - Hybrid engine operation
  - 1 fill per day
  - Pipeline NG filling
- Key questions
  - Critical to customer issue identification
  - Clarify regulatory path-to-market
  - Finalize product prototype parameters
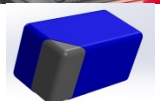
➤ **Prototype demonstration Q1/2016**
- Final deliverable
- Form, fit, and function of target 1st product (incl. regulatory compliance)



- ✓ Lower Pump Cost
- ✓ Improved Safety
- ✓ Payback period <12 months
- ✓ Tank size/shape according to application
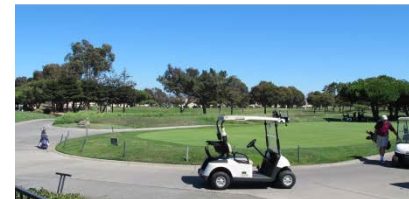


First Demonstration
Monarch Bay
Golf Course
San Leandro CA
February 2015

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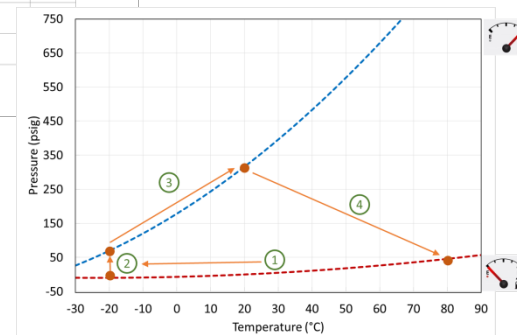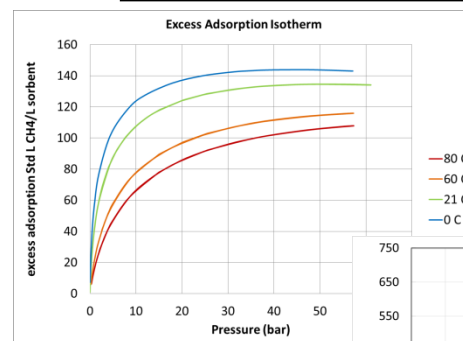Tel: 415-273-6808
Email: dkirkpatrick@blackpaktech.com

## Accomplishments

- Validated pathways to <$5/kg sorbent
  - Commodity precursors with diverse supply chain
  - Initial
- Regulatory driver for ANG is Maximum Developed Pressure (MDP) at 80C
  - ANG pressure rise w/ temperature far exceeds linear behavior of CNG
  - $\kappa_T$(carbon monoliths) » $\kappa_T$(natural gas), therefore relevant $T_{max}$ = 80C (not 57C)
  - Significantly increased pressure testing requirements
  - Places much greater challenge on encapsulant
- Developed and demonstrated new fill pump strategy ("tank-as-pump")
- Local municipal golf course partner for concept & prototype demonstrations
  - Operating company runs 90 other courses
  - Potential for <12-month payback is critical
  - Expect initial entry will be mostly retrofit markets
- California Energy Commission project selected for Light Duty Vehicle demo

### <$5/kg Sorbent Pathways Validated



### Tank-as-Pump Breakthrough

# Containerless Natural Gas Storage

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## Transition

> **Three-fold transition strategy**
> - Initial introduction into mower market
> - Expansion into forklift and scooter markets
> - Prototype development for light duty vehicle market
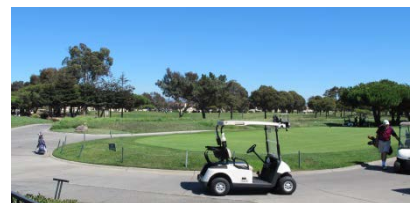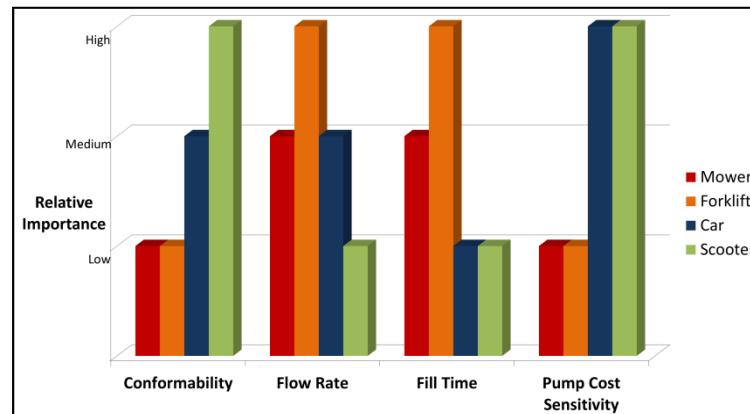
> **Current focus: go-to-market partnerships**
> - Golf course operations management companies
> - Distribution center management companies

> **Funding needs**
> - Mower market rollout – $4-10M, initially as a service
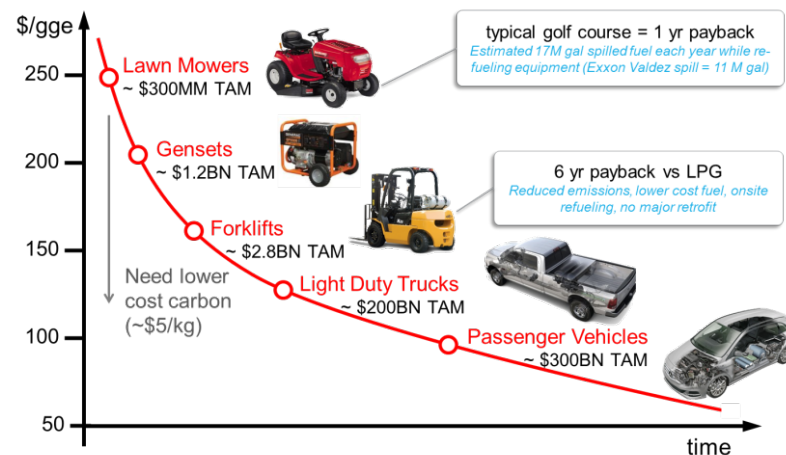> - Forklift or scooter prototype effort - $2-4M

> **Funding strategy**
> - Contracted partnerships for market entry
>   - Partner-funded
>   - Partner-contract backed
> - Prioritize near-term accessible markets
>   - Retrofit
>   - Small to mid-scale
>   - Drive to FCF +ve



Relative Importance chart (Mower, Forklift, Car, Scooter) across Conformability, Flow Rate, Fill Time, Pump Cost Sensitivity



Why golf course mowers?
- 15,500 US courses in 2012
  - 11,000 public
  - 4,500 private
  - ~100 acres/course
  - 1.5M gal fuel consumed/day
- Annual fuel budget: ~$35K-$145K/course
- $150-300M TAM w/ <12 mo return



- Lawn Mowers ~ $300MM TAM
  - typical golf course = 1 yr payback
  - Estimated 17M gal spilled fuel each year while re-fueling equipment (Exxon Valdez spill = 11 M gal)
- Gensets ~ $1.2BN TAM
- Forklifts ~ $2.8BN TAM
  - 6 yr payback vs LPG
  - Reduced emissions, lower cost fuel, onsite refueling, no major retrofit
- Light Duty Trucks ~ $200BN TAM
- Passenger Vehicles ~ $300BN TAM
- Need lower cost carbon (~$5/kg)

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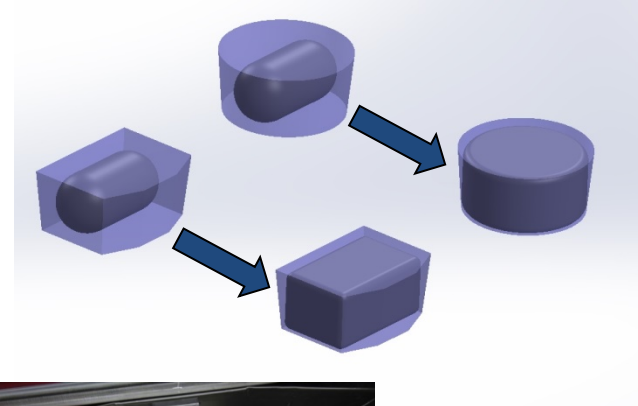Email: dkirkpatrick@blackpaktech.com

**Transition – CEC Project**

Objectives:

- 6 MJ/liter at 500 psi pressure minimum (target 7 MJ/liter)
- Fuel-tank system cost <$200/GGE (assuming mfg volume >1000 units/month
- Fill/refill cycle life >1000 cycles at >80% capacity retention
- Conformable (>90%)
- Compatible with the full range of vehicle engine operating requirements
  - Idle to full acceleration
  - Electrical system loading
- Meet/exceed initial safety and reliability
  - Burst,
  - Impact, and
  - Bonfire testing

Timeline: 24 months

Objective platform: Light duty vehicle (consumer focus)



Mini Cooper

Ford Focus

Ford Edge

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## Transition – CEC Project

➢ **Highlight challenges**
- Cycle testing – at least 100 cycles from pipeline NG with a target of 1000 cycles
- 90% volumetric efficiency
- 6MJ/liter minimum
- Full burst, impact, and bonfire testing
  - Impact to include medium-cal AP-incendiary
  - Baseline comparison w/ COTS CNG
  - Detailed modeling and analysis of results

➢ **Tank-as-pump to be evaluated & included**
- Cost base not included in $200/GGE system
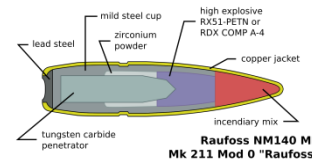
➢ **Gas – natural gas hybrid configuration**
- Eliminate range anxiety
- Target maximum utilization
  - Single car households
  - Retrofit capable

➢ **Stationary testing only**
- Dynamometer configuration
- Pre-certification testing parameters
- On-road testing not anticipated (even closed track)



SRI rupture and deflagration test on pipeline with flame column rising to more than 1,000 feet high



lead steel | mild steel cup | zirconium powder | high explosive RX51-PETN or RDX COMP A-4 | copper jacket | incendiary mix | tungsten carbide penetrator

Raufoss NM140 MP
Mk 211 Mod 0 "Raufoss"

M48 Spotter/Tracer (yellow/red) | M1 Incendiary (light blue) | M17 Tracer (Burgundy) | M20 Armor Piercing Incendiary Tracer (red/silver) | M8 Armor Piercing Incendiary (silver) | M2 Armor Piercing (black) | M33 Ball (natural) | Raufoss Mk211 mod 0

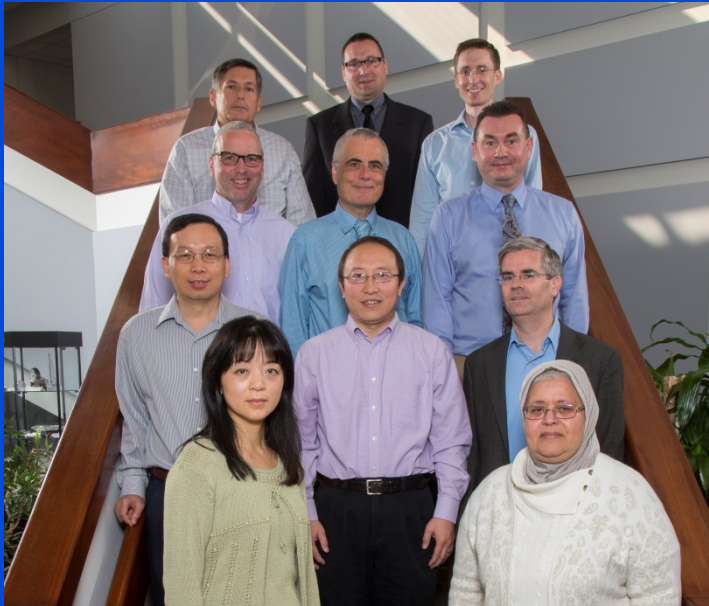Aerial view of SRI's large-scale flammable gas release facility (CHES)

# Low Cost Materials and Manufacturing for Conformable CNG Tanks

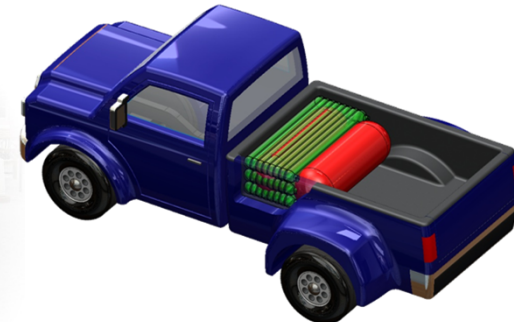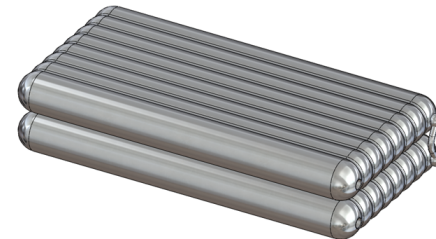United Technologies Research Center

Dr. Ellen Sun

(860) 610-7262, suney@utrc.utc.com

- Modular conformable design for spaces with aspect ratios ranging from 1:4:10 to 1:1:5

- Design applicable to a variety of commercially available materials (composites, high strength aluminum, and steel)

**Team:**

Tom Garosshen, Andrzej Kuczek, John Sharon
Paul Croteau, John Wesson, Justin Hawkes,
Joe Liou, Wenping Zhao, Andrew Dasinger,
Ellen Sun, Tahany El-Wardany,
Jim Irish, Matt Lynch, and Dan Viens,

**United Technologies Research Center**

# Low Cost Materials and Manufacturing for Conformable CNG Tanks

United Technologies Research Center

Dr. Ellen Sun

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| | Type I | Type IV | MOVE Goal | UTRC Objective | | |
| --- | --- | --- | --- | --- | --- | --- |
| | | | | Composite | Al | Steel |
| Conformability (%) | 58-66 | 50-60 | >90 | **71** | **72** | **79** |
| Energy density (MJ/L) | 5.7-6.5 | 5.0-6.0 | >8.9 | **7** | **7.1** | **7.9** |
| Specific Energy (MJ/kg) | 6.6-7.8 | 16-22 | >12 | **17** | **11** | **8** |
| Tank Cost ($/GGE) | 38-45 | 147-225 | <150 | **134** | **174** | **159** |

- Completed steel and composite sub-scale prototype fabrication

- Completed first steel sub-scale prototype pressure testing

- Filed 5 patent applications

| Test Sequence | |
| --- | --- |
| 0 - 3600 psi | 1 cycle |
| 0 - 4500 psi | 1 cycle |
| 0 - 5400 psi | 1 cycle |
| **360 – 4500 psi** | **100 cycles** |
| 0 – 7668 psi | 1 cycle |
| 0 – 7900 psi | 1 cycle |
| **0 – 8100 psi** | **burst** |
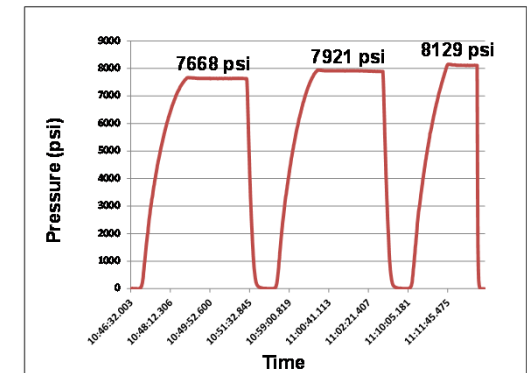
# Low Cost Materials and Manufacturing for Conformable CNG Tanks

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## Project Key Milestones

- Q4 2013…Concept demonstrated via critical elements;
  Market needs understood and IP strategy established
- Q4 2014…Subscale demonstration;
  Value proposition established and OEM engaged
- Q4 2015…Full scale prototype validation;
  Business option and potential partners established

## Year 3 Goals

- Complete full scale prototype fabrication

- Complete pressure testing and cycling testing of the prototype

- Establish technology-to-market path

## Expectation for This Annual Meeting

- Interaction with OEMs and QVMs

- Better understanding of tank-vehicle integration requirements

- Better understanding of regulatory requirements for non-cylindrical tanks

- Opportunities beyond MOVE for NGV-2 required tests & vehicle demonstration

**United Technologies Research Center**

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# The Matrix Tank™



REL, Inc.
Dr. Adam Loukus, Vice President
(906)370-2326  adam@relinc.net

## REL Team & Advisors



| | | | | | |
|---|---|---|---|---|---|
| Robert E. Loukus<br>Co-Founder<br>Custom Machining | Josh Loukus, PhD<br>President<br>Custom Equipment | Adam Loukus, PhD<br>Vice President<br>Advanced Materials | David Rowe<br>REL, CFO & VP<br>Business Development | Steve Benda<br>REL, Director<br>IP & Patents | William Calvert<br>Advisor/Consultant<br>Industry Expert |
| Luke Luskin<br>Sr. Engineer | Travis Pennala<br>Engineer | Brent Halonen<br>Analyst | Andrew Halonen<br>Sales Engineer | David Bekkala<br>Manager | David Weiss<br>Technical Advisor<br>Eck Industries |

# The Matrix Tank™

REL, Inc.
Dr. Adam Loukus, Vice President
(906)370-2326 adam@relinc.net

**Innovation**

## Structural & Volumetric Efficiency

### Structure Inspired by Nature

### 20-35% Greater Storage Capacity



*Utilizes Wasted Space*
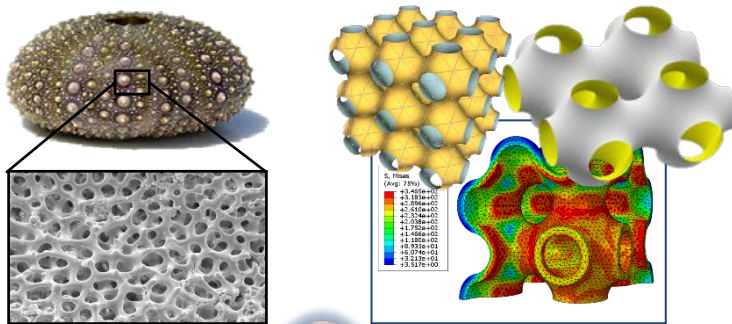
Seamless Integration of Tank Skin
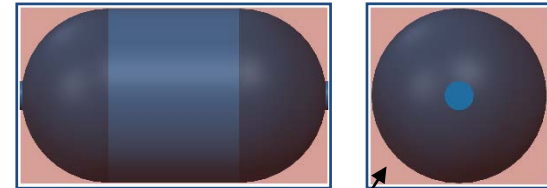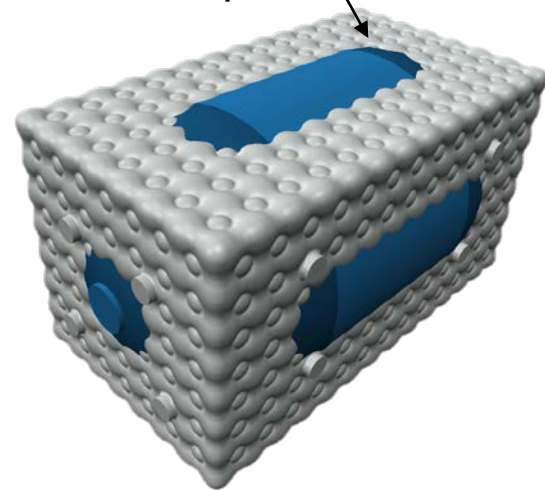
Rectangular v. Cylindrical Volume

# The Matrix Tank™

**MATRIX**

## Objectives

## Technical Targets
- 10" x 20" x 40" (~9 GGE) tank
- 8100psi burst pressure
- Cycle testing; other required testing

## Key Challenges
- Develop high integrity metal casting process
- Alloy selection for castability & tank performance metrics

## Metrics

| | | MOVE Targets | REL Current | REL Optimized |
|---|---|---|---|---|
| Conformability | % | > 90 | 68.1 | 75.5 |
| Energy Density | MJ/L | > 8.9 | 6.74 | 7.48 |
| Specific Energy | MJ/kg | > 12 | 7.9 | 11.87 |
| Tank Cost | $/gge | < 150 | < 141-183 | < 87-107 |
| Material Cost | $/gge | < 75 | 72 | 68 |
| Burst Pressure | MPa | ~ | 31 | 55.8 |
| Container Temperature | °C | -40-85 | -40-85 | -40-85 |
| Max Stress | psi | ~ | 45000 | 67500 |
| Codes & Standards | | ~ | ANSI NGV2** | |

*REL Current: Quarter-Scale (11.25x11.25x20.25) 1.5 cell size, 0.15 wall & web*
*REL Optimized: Full-Scale (10.22x19.23x41.73) 2.25 cell size, 0.15 wall & web*
*\*Tank Cost dependant on testing required*
*\*\*Tank testing specification for one-piece cast aluminum tank is TBD*
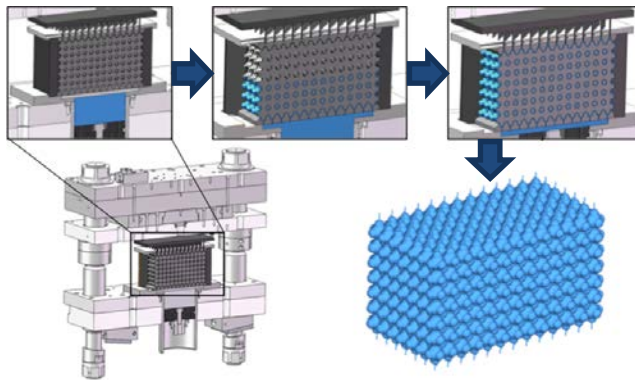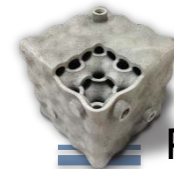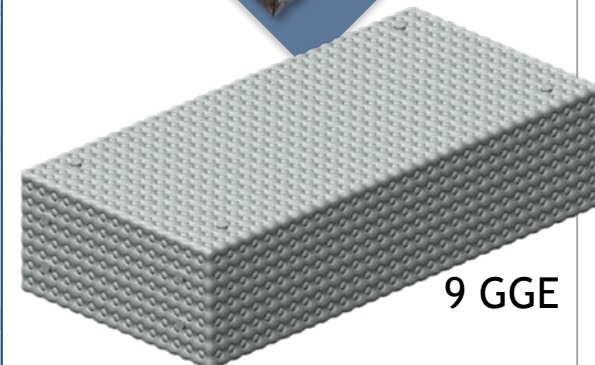
# The Matrix Tank™

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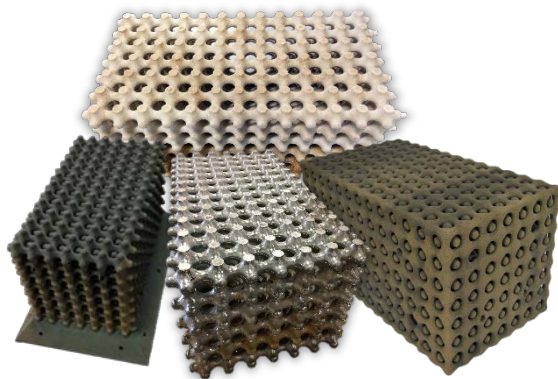(906)370-2326 adam@relinc.net

**Accomplishments**

## "That's Impossible…"

Cubic     Schwarz-P     Optimized Wall     Quarter Scale
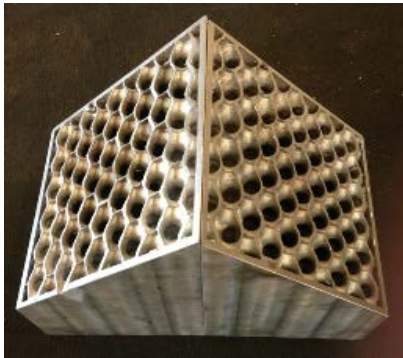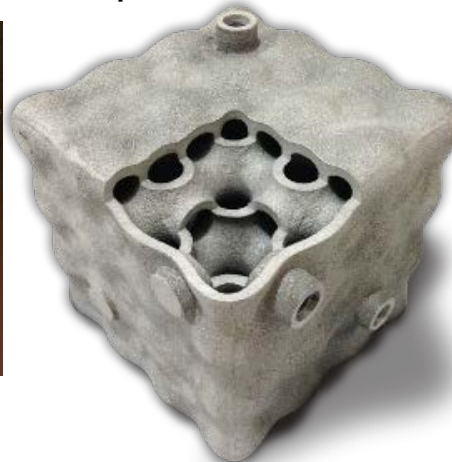


## Tech-to-Market (T2M): Focus on Vehicles
### Which Vehicles Need a Conformable Tank?

- Poor Mileage, Premium Cargo Space & High Fuel Costs
- Limited Range

# The Matrix Tank™

REL, Inc.
Dr. Adam Loukus, Vice President
(906)370-2326 adam@relinc.net

**Transition**

## Current Funding:
Tank Development, Vehicle Integration & Manufacturing Design:
- $3.75M: Department of Energy ARPA-e Award & Cost Share
- $2.00M: Department of Energy ARPA-e Plus-Up Request
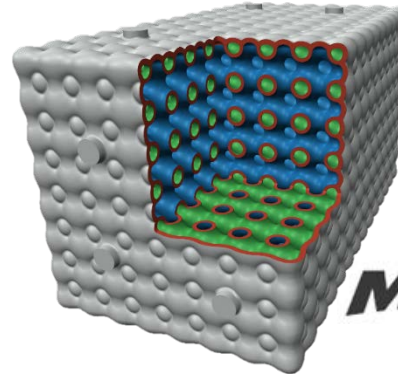- $2.00M: Michigan Tech University / SWN Demonstrator Build

## Investment:
Establishment of a Manufacturing Facility:
- Stage 1 – $10.6M – Year 1
- Stage 2 – $3.1M – Year 3

## Needed from Audience:
- Joint Venture – Vehicle Integration, Capital, Sales/Marketing, Distribution
- Testing Requirements

Award Winning Company